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Restructured Freedom
Configuration Characteristics

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Introduction

In January of 1991, the LaRC SSFO performed an assessment of the characteristics of the proposed pre-integrated Freedom concept. Of particular concern was the relationship between solar array operation and spacecraft controllability. For the Man-Tended configuration (MTC), it was determined that torque equilibrium attitude (TEA) seeking CMG control laws could not always maintain attitude using four CMGs. Control problems occurred when the solar arrays were tracking the sun to produce full power while flying in an arrow or gravity gradient flight mode. At these attitudes, high rate alpha joint motion may occur during an orbit when the direction to the sun is nearly parallel to the alpha joint rotation vector. This in turn leads to significant variations in configuration inertia, thus 1) invalidating constant inertia control gain derivation assumptions, and 2) exerting a disturbance torque on the CMG controlled core body. Several modified sun tracking techniques were evaluated with respect to producing a controllable configuration requiring no modifications to the CMG control algorithms. A feathered flight attitude produced satisfactory control characteristics but reduced available power from 18.75 kw to an average of 8.7 kw. Other constrained sun tracking strategies eliminated the large solar array articular motions and the associated controllability problems while only reducing full power by an average of up to 10%. Another assessment involved the asymmetric Permanently Manned Configuration (PMC) which has a third PV unit on one side of the transverse boom. Results indicated that this configuration would utilize almost two-thirds of the CMG momentum storage capability at an orbital altitude of 220 nautical miles. Other simulations indicated that the addition of a berthed orbiter utilized nearly all of the available CMG capability.

This report summarizes the above study. Report recommendations include constraining alpha rotations for MTC in the arrow and gravity gradient flight modes and perhaps developing new non-TEA seeking control laws. Recommendations for PMC include raising the operational altitude, or moving to a symmetric configuration as soon as possible.

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OBJECTIVES

Following the restructuring exercise completed in January, 1991, significant changes in power and flight orientation for key Space Station *Freedom* configurations compared to the existing baseline were noted. For example, the Man Tended Configuration (MTC) may operate with the photovoltaic (PV) arrays *locked* ((i.e., non sun–tracking) in an *arrow* attitude (i.e., with the truss along the velocity vector[1]. Hence, one objective of this study was to determine the power loss resulting from this orientation. Further, when attached to the Orbiter, the MTC is flown in a gravity gradient (GG) attitude, with PV arrays fully sun–tracking. Thus, a second objective of this study was to determine the stability and controllability characteristics of the MTC in a GG mode both with and without the attached Orbiter.

The restructured Permanently Manned Configuration (PMC) is to operate with 56.25 kW of power to be obtained from 3 pairs of PV arrays[1]. Level 2 proposes an asymmetric configuration whereby two array pairs are on the starboard side of the configuration, with the remaining pair are on the port side. Thus, a third objective was to ascertain the controllability characteristics of the asymmetric PMC configuration. For comparison purposes, a symmetric 75kW PMC configuration with 4 array pairs is also examined for controllability characteristics.

1) Recommended Program Content Overview, M. Bensimon, Jan 29, 1991.

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Technical Assessments

The first half of the study assessed the flight characteristics of the Man Tended Configuration (MTC). In particular, the attitude controllability characteristics and the power generation capability both with and without the attached Orbiter were analyzed.

All attitude control sizing studies performed assumed the PDRD *design* atmosphere : solar flux = 230: geomagnetic index = 140 (microgravity environment calculations were performed assuming assembly date nominal atmospheres). All studies were performed assuming an altitude of 220 Nautical miles (except for the Appendix which assumed a 190 Nm altitude)

Technical Assessments

- **Man Tended Configuration (MTC)**
  - Attitude Controllability vs Power Generation Capability
  - With and Without Attached Orbiter

- **Permanently Manned Configuration (PMC)**
  - Attitude Controllability with Asymmetric Geometry
  - With and Without Attached Orbiter

MTC Configuration

Early SSF assembly configurations may be flown in a gravity gradient attitude, with the transverse boom along the nadir direction, or, in an *arrow* attitude, with the transverse boom along the velocity vector. Both of these attitudes effectively interchange the roles of the alpha and beta joints in the sense that the inner (alpha) joint no longer primarily compensates for the orbital motion; nor does the outer (beta) joint primarily compensate for the solar beta angle that arises when the direction from the spacecraft to the sun lies outside of the orbit plane. Although there are no known hardware or software problems anticipated for such a joint role reversal, the resulting alpha-beta motion required to fully sun-track gives rise to significant variations in SSF mass properties, which introduces attitude controllability problems. In particular, the JSC/UT CMG control laws compute constant gain coefficients presuming constant inertial properties, which may not yield stable control characteristics in the presence of significant mass variations. Even the gravity gradient attitude is not 3 axis stable over an entire orbit due to changes in the inertia which occur when sun-tracking.

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MTC Configuration

- Early restructured SSF assembly configurations may be flown in "gravity gradient" or "arrow" orientations, with the transverse boom along the nadir direction, or velocity direction, respectively.

- This effectively interchanges the roles of the alpha and beta joints. According to NASA LeRC, there are no known hardware or software problems anticipated for either joint to sun-track while in these orientations.

- However, because the alpha-beta motion gives rise to significant variations in mass properties, the so-called *gravity gradient* attitude is not 3 axis stable over an entire orbit. In particular, it can become unstable in roll-yaw. Furthermore, the JSC/UT CMG control law implementation is not designed to accommodate the relatively large inertia variations associated with either orientation.

MTC IN THE ARROW FLIGHT MODE

The figure depicts the restructured Man Tended Configuration flown with the transverse boom along the velocity vector direction in the so-called *arrow* mode. Note that the inner, or alpha, axis is also aligned with velocity, while the outer, or beta, axis is perpendicular to the orbit plane. Orbital reboost maneuvers will likely impinge on both the thermal radiator, as well as the pressurized modules. Attitude control during reboost must also be studied.

MTC IN THE ARROW FLIGHT MODE


VELOCITY

P O L

NADIR
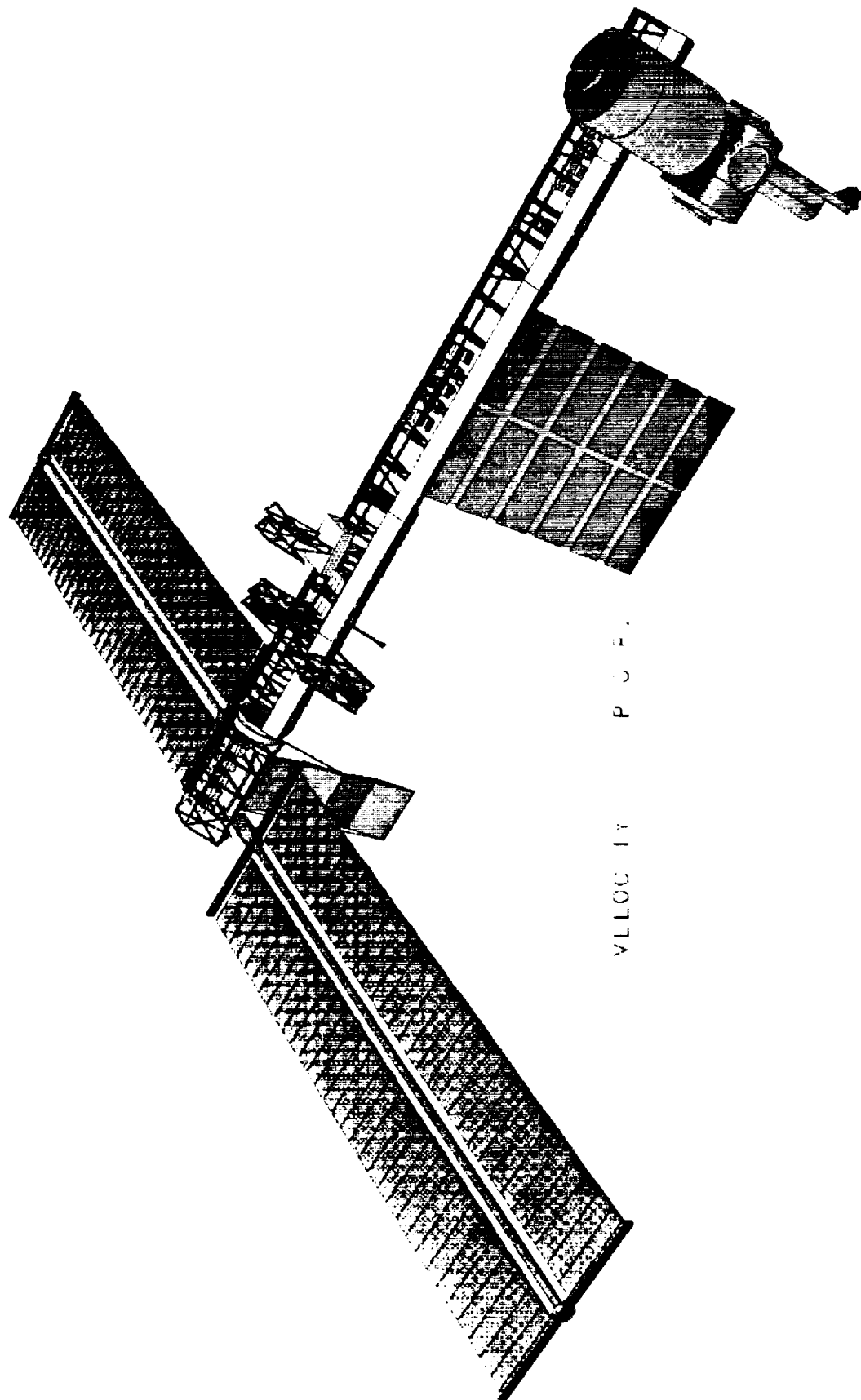
MTC and Orbiter in the Gravity Gradient Flight Mode

The figure illustrates the MTC configuration flown in a gravity gradient attitude with the attached Orbiter. The arrays are assumed to be sun-tracking in order to obtain the full 18.75 kW of power. Note the the Orbiter approaches and docks with the MTC configuration along the minus V-bar (velocity) direction.

MTC and Orbiter in the Gravity Gradient Flight Mode

Velocity

P.O.P.

Nadir
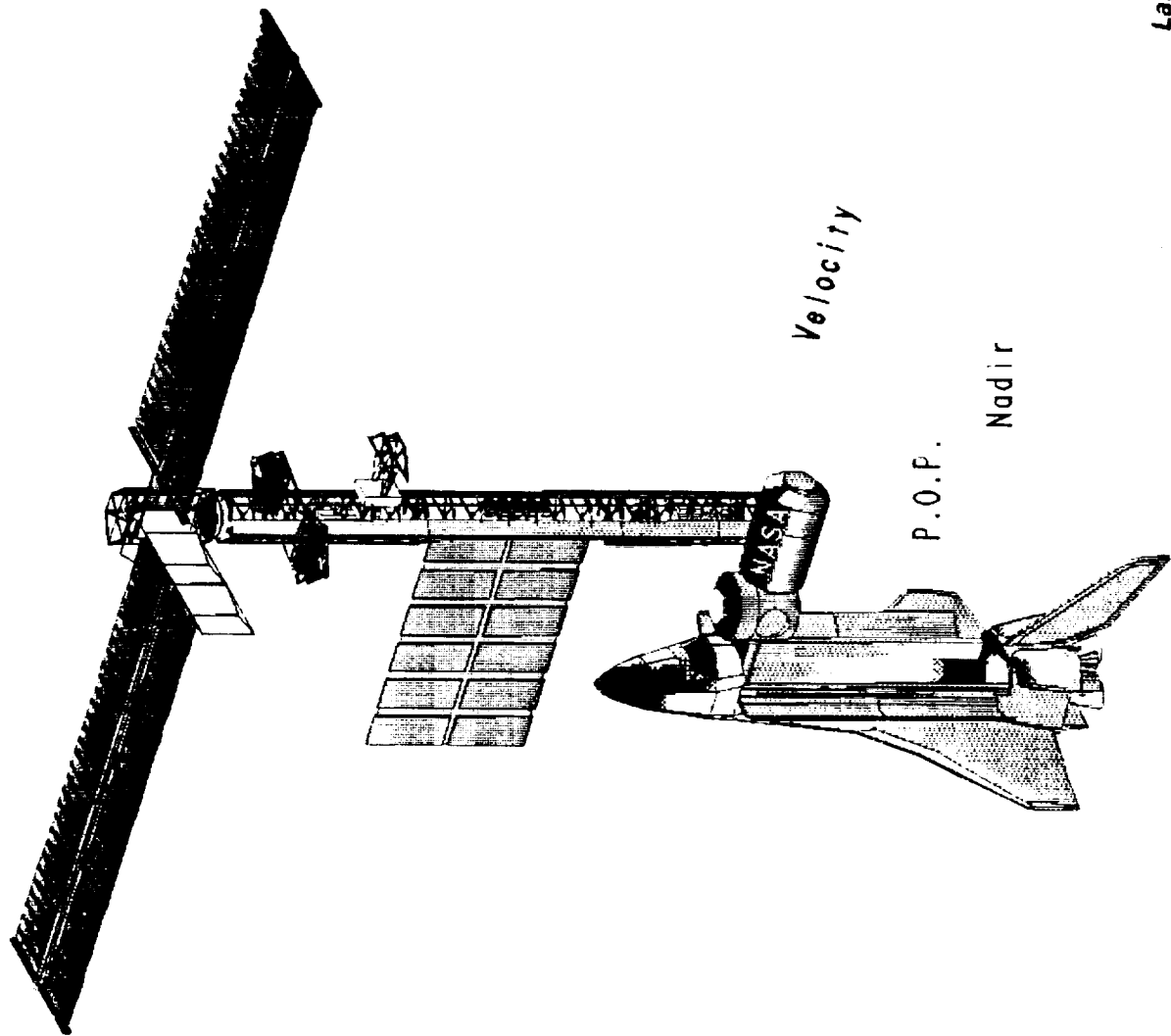
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MTC (continued)

The restructured MTC flown with the arrays locked in a feathered orientation (either arrow or gravity gradient) is easily controllable. However, the power loss is significant. Of the 18.75 kW capacity, only 8.7 kW annual average power is provided.

The JSC/UT CMG controller with the control gains evaluated using generic pole placements techniques proposed by Sunkel. et.al., could not control the MTC configuration in *any* attitude while sun-tracking with the photovoltaic arrays. Preliminary RCS control analyses exhibited prohibitive propellant requirements to maintain attitude control.

A "semi sun-tracking" strategy was successfully used in simulating the Earth orbiting MTC station. whereby only the alpha (or inner) axis is locked. and the beta (or outer) axis rotates at orbit rate. Although this strategy does not fully sun-track. the average annual power is on the order of 17kW, i.e., about a 10% power reduction compared to full sun-tracking. Furthermore. the configuration is controllable flown in either arrow or gravity gradient mode. since there are no large inertia variations over an orbit.

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MTC (continued)

- Restructured MTC may be flown with arrays locked in a feathered orientation. This is easily controllable, but results in a significant power reduction. In particular, of the 18.75 kW capacity, only 8.7 kW (annual average) is realized.

- The JSC/UT CMG controller with the control gains evaluated using generic pole placement schemes could not control the MTC configuration while sun-tracking. (Preliminary RCS control exhibits prohibitive propellant requirements)

- A "semi–sun–tracking" strategy is proposed for MTC free–flyer configurations and earlier, whereby only the alpha axis is locked, and the beta axis rotates at orbit rate. This configuration is controllable (no large inertia variations), and results in only a 10% power reduction compared to full sun–tracking, e.g., 17 kW average annual power. Either the arrow or the gravity gradient orientation can be maintained.

Yearly Power Variation for MTC in Arrow Flight Mode

With the photovoltaic arrays locked and non-articulating, the amount of power available depends on the MTC-sun relative geometry, which varies over an orbit, and over a year, due to nodal regression of the orbit. The plot shows the yearly power available (in kW) over the 365 day year. As can be seen, the average power during certain times of the year is as low as 5.3 kW, or as high as 9.75 kW. The average available power over the entire year is approximately 8.7 kW.

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Yearly Power Variation for MTC in Arrow Flight Mode with Locked Alpha and Beta Gimbal Angles (Feathered)
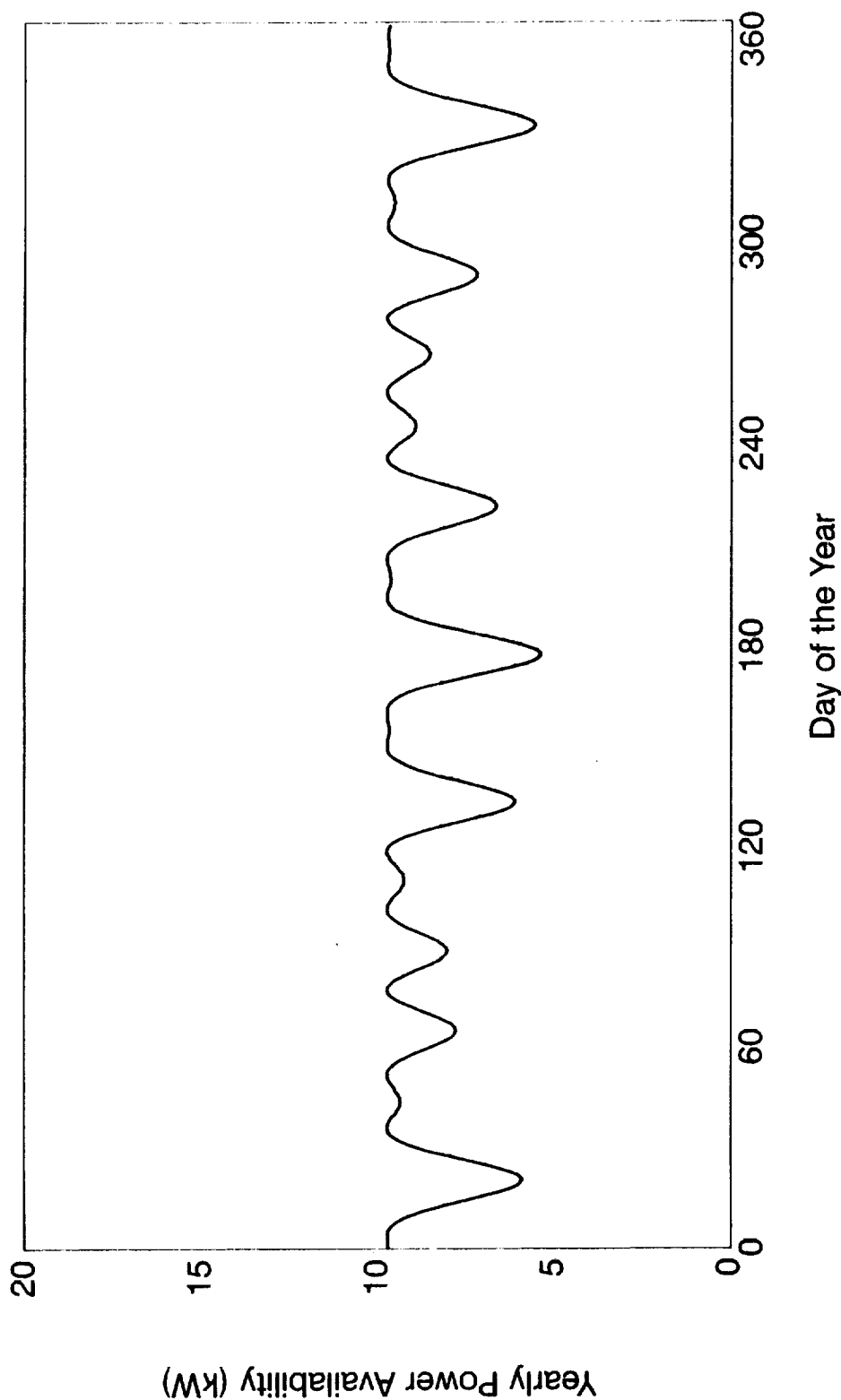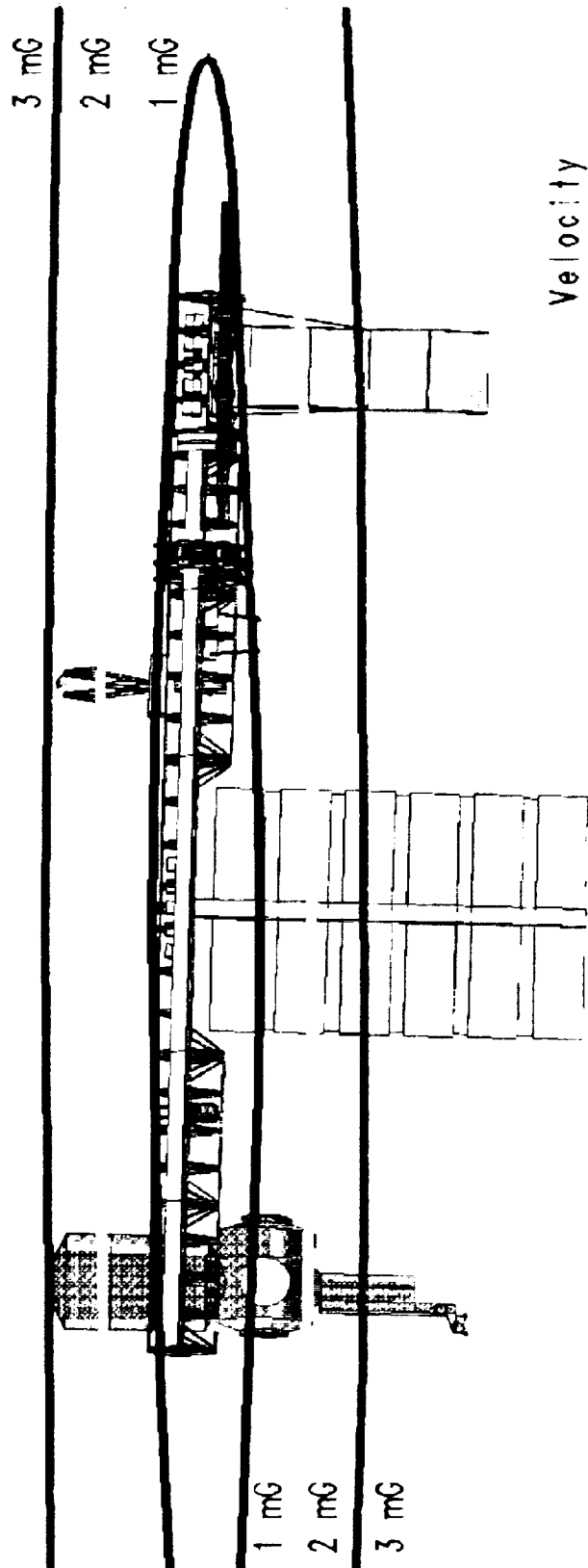
1. LVLH attitude assumed .
2. Yearly average available power is approximately 8.70 kW.
3. Minimum available power is 5.30 kW and maximum available power is 9.75 kW.

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Man-Tended in the Arrow Flight Mode (Feathered Arrays)
Micro-G Environment

The figure opposite depicts the microgravity environment for the MTC configuration flown in the arrow flight mode. A nominal atmosphere on the nominal launch date of December. 1996 is assumed. at a nominal altitude of 220 Nm. The arrow mode puts the pressurized volume in a favorable 1 to 2 micro-G environment.

Man-Tended in the Arrow Flight Mode (Feathered Arrays)

Micro-G Environment

3 mG
2 mG
1 mG

Velocity

1 mG
2 mG
3 mG

Date = 12/96   Alt = 220 nmi
Flux = 71.9   Ap = 12.4

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Man-Tended With Attached Orbiter (Sun-Tracking Arrays)

This figure depicts the microgravity environment of the mated Orbiter-MTC configuration. Although most of the MTC is well outside of the desirable micro-G environment. the pressurized volume still falls within the 1 to 2 micro-G region due to the massive Orbiter docked directly to it. As before. nominal altitude. atmosphere. and launch date are assumed.

Man-Tended With Attached Orbiter (Sun-Tracking Arrays)

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1 mG

3 mG

Date = 12/96   Alt = 220 nmi
Flux = 71.9   Ap = 12.4

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MTC Arrow – Yearly Power Variation with Beta-Tracking only

The figure shows the variation in average power over a year beta-tracking only. An LVLH attitude is assumed. with the alpha axis locked. and the beta axis rotating at orbit rate. Except for certain geometry conditions. this results in less than the full 18.75 kW sun-tracking power. As can be seen. minimum available power during the least favorable sun geometry conditions can be as low as 11.54 kW. However. the average annual available power is on the order of 17 kW. an approximate 10% reduction compared to full sun-tracking.

MTC Arrow – Yearly Power Variation with Beta–Tracking only

NASA FREEDOM

Yearly Power Availability (kW) (y-axis: 0, 5, 10, 15, 20)

Day of the Year (x-axis: 0, 60, 120, 180, 240, 300, 360)
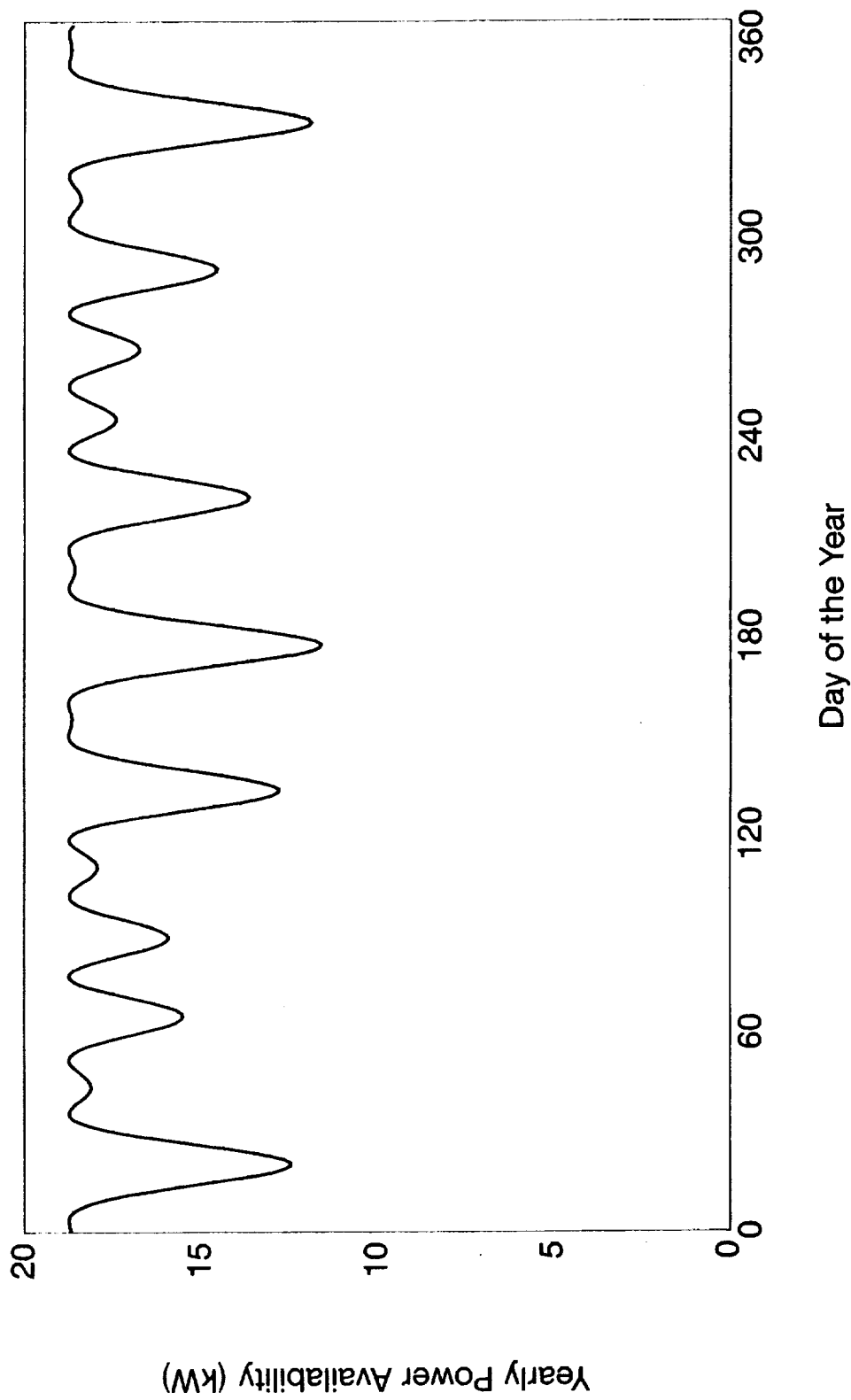
1. LVLH attitude assumed with locked alpha & optimal beta gimbal strategy.
2. Yearly average available power is approximately 17.05 kW.
3. Minimum available power is 11.54 kW and maximum available power is 18.75 kW.

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MTC (concluded)

An alternate technique was evaluated to obtain more power while avoiding the controllability problems associated with full sun-tracking. The concept was to utilize the alpha joint to make small periodic adjustments to more nearly sun-track. without undergoing large inertia variations. However. this approach was unsuccessful for two reasons. First. the PV array moments of inertia are significant when compared to the core body; and as a consequence. alpha rotations of the PV arrays tended to re-align the principal body axes and thus alter the torque equilibrium attitude. The net result was that the MTC configuration always tended to have a steady state attitude with the PV arrays aligned either perpendicular to the orbit plane. or horizontal. Secondly. to take advantage of small alpha angle offsets requires non-orbit rate beta motion. which implies the need for customized beta control algorithms.

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FREEDOM

MTC (concluded)

- **Fixing alpha at an "optimal" constant value for several orbits, and then making periodic small adjustments, does not work**

  - The resulting torque equilibrium attitude tends to re-align the arrays along nadir.

  - Optimal beta gimbal angle commands are *not* orbit rate, and thus require customized controllers.

CMG Characteristics and Attitude Rate Limits

There are 4 Control Moment Gyroscopes manifested for assembly flight 2; however, the supporting avionics to activate and control the CMGs will not be available until assembly flight 5. Each CMG has an angular momentum capacity of 4745 Newton-meter-seconds.

Using a torque equilibrium attitude seeking CMG control law algorithm results in periodic oscillations in space station attitude rate over each orbit. Large attitude rates adversely affect the microgravity environment due to rotation accelerations. In particular, rates in excess of 0.01 deg/sec noticeably shrink micro-g envelopes. Rates as large as 0.1 deg/sec begin to cause concern about the capability to perform proximity operations, berthing, and docking.

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CMG Characteristics

- 4 CMGs manifested Flight 2

- CMG Capacity : 4745 N–M–S each

- Not utilized until flight 5 ! (– GN&C "white paper"

Attitude Rate Limits

- > 0.01 deg/sec : Begins to degrade microgravity environment

- > 0.1 deg/sec : Begins to degrade rendezvous capability
  (speed of minute hand)

MTC Control Characteristics

The table summarizes the control characteristics of the Man–Tended Configuration. The first column lists the variations studied : 1) arrow (locked arrays), 2) arrow (sun–tracking arrays), 3) gravity gradient (locked arrays), 4) gravity gradient (sun–tracking arrays), 5) arrow (semi–sun tracking arrays), and 6) gravity gradient with attached Orbiter (sun–tracking). All results were calculated assuming a 220 Nm altitude. Control studies assumed the space station design atmosphere; microgravity computations assumed a nominal day of launch atmosphere.

The second column depicts the Torque Equilibrium Attitude, or TEA. The arrow configurations have a slight yaw angle TEA (~ −6 degrees) due to the location of the pressurized node. The gravity gradient configurations all have a modest roll TEA (~ 5 deg) due to the same reason. The introduction of the sun–tracking to the gravity gradient configuration induces a 9.5 degree pitch TEA due to aerodynamic torques. The attached Orbiter further increases the pitch TEA to over 13 degrees, with 4 to 5 degree variations in roll and yaw as well.

Column 3 summarizes the average available power in kilowatts. The two locked array configurations yield the lowest power as expected. The configurations with full sun–tracking yield 18.75 kW of power (if they could be controlled). The semi–sun tracking strategy simulating beta tracking only (orbit rate is the optimal solution) yields on average 90% of full sun–tracking power (17.0 kW).

Column 4 lists the ballistic coefficient (kg/m^2). The arrow configuration with locked arrays exposes the minimal surface to the velocity vector resulting in a relatively large ballistic coefficient of 150. Similarly, the locked array gravity gradient configuration yields a ballistic coefficient of 128.7. With articulating arrays, the ballistic coefficient drops down to 43 to 47, with the exception of the mated Orbiter configuration, whose mass increases the ballistic coefficient to 79.5. The semi–sun tracking strategy yields a 55.1 Kg/m^2.

The angular momentum requirements are depicted in column 5. The MTC arrow configuration with locked arrays, although unstable, requires minimal control. However, allowing the arrays to sun–track in an attempt to increase power results in the

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MTC Control Characteristics (220 Nm altitude; design atmosphere)

Configuration	Avg. Flight Attitude from LVLH (deg) (yaw, pitch, roll)	Avg. Annual Power (kW)	Avg. Ballistic Coef. (kg/m^2)	Peak Ang Mom Req'd SS/(max) (N–m–s)	Peak Angular Rates (deg/sec)	Lab Microg. Environ. (µg)
MTC, Arrow, (locked arrays)	(–6.0, –1.3, 0.0)	8.7	150.0	200 (500)	< 0.001	1–3
MTC, Arrow, (sun–tracking arrays)	(–6.1, –0.1, 0.9)	18.75	43.7	*	*	
MTC, Gravity Gradient (locked arrays)	(–2.5, 0.2, 5.6)	< 8	128.7	none (passive)	± 0.01	
MTC, Gravity Gradient (sun–tracking arrays)	(–2.3, 9.5, 5.2)	18.75	46.9	*	*	
MTC, Arrow (semi–sun–tracking)	(–6.1, –1.0, 0.9)	17.0	55.1	2500 (5000)	± 0.02	<2
MTC, Gravity Gradient (sun–tracking) w/STS	(4.0, 13.4, 5.4)	18.75	79.5	5000 (10,000)	±0.02	< 2

Gravity gradient, sun–tracking configurations are not stable.
Significant power reduction for non–articulating arrays.
Semi sun–tracking is controllable and yields reasonable power.

* not controllable using JSC/UT CMG control law

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MTC Control Characteristics
(continued)

earlier mentioned large inertia variations which cause controllability problems to the JSC/UT CMG control laws. Likewise, the gravity gradient configuration is 3-axis stable with locked PV arrays; however, full sun-tracking induces controllability problems. Preliminary analysis revealed that even using RCS jets for attitude control requires prohibitive amounts of propellant. The semi-sun tracking strategy results in acceptable peak angular momentum control requirements on the order of 1 CMG to supply steady state attitude control. The addition of the Orbiter to the gravity gradient sun-tracking configuration introduces a degree of stability due to the added mass – although controllable, significant peak momentum requirements (10.000 N-m-s) were encountered.

Column 6 lists the peak angular rates encountered over an orbit. The CMG controlled arrow MTC configuration was very stable with rates less than 0.001 deg/sec. The *uncontrolled* gravity gradient configuration had rates on the order of $\pm$ 0.01 deg/sec which could be reduced to the same magnitude as the arrow flight configuration using CMG control. Both the semi-sun tracking MTC, and the gravity gradient configuration with attached Orbiter exhibited pitch oscillations on the order of $\pm$ 0.02 deg/sec over an orbit.

The last column summarizes the microgravity environment in the pressurized lab for the Level 2 proposed MTC configurations : arrow (non-man-tended), and gravity gradient (attached Orbiter). The values for all cases ranged from 0 to 3 micro-Gs.

Based on the results presented in the table, it was noted that the non-articulating array configurations resulted in significant power reductions (> 50%) when compared to articulating arrays, as expected. Three CMGs (capacity of 4745 N-m-s each) are required for steady state attitude control with the Orbiter attached to the MTC configuration (full sun-tracking). Free-flying sun-tracking MTC configurations are neither stable nor controllable using the described control algorithms. Reduced sun-tracking strategies, such as beta tracking only, overcomes controllability issues while still delivering adequate power.

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MTC Mass Inertia Properties

The table depicts the variation in moments and products of inertia for the configurations analyzed.

MTC Mass Inertia Properties

Configuration	Moment of Inertia x10^6 (Kg-met^2)			Product of Inertia x10^5 (Kg-met^2)		
	Ixx	Iyy	Izz	Ixy	Ixz	Iyz
MTC, Arrow, (locked arrays)	2.6	19.5	20.6	18.1	-4.8	-0.6
MTC, Arrow, (sun-tracking arrays)	2.2 to 2.6	19.4 to 20.5	19.2 to 20.6	17.9 to 19.7	-3.4 to -4.8	-6.8 to 4.3
MTC, Gravity Gradient (locked arrays) *	15.6	17.1	2.3	0.1	0.2	1.3
MTC, Gravity Gradient (sun-tracking arrays) *	16.3 to 16.7	15.7 to 16.0	2.0 to 2.1	-2.2 to 4.4	3.2 to 3.7	13.2 to 13.7
MTC, Arrow (semi-sun-tracking)	2.6	19.5	20.5	18.2	-4.7 to -4.8	-0.6
MTC, Gravity Gradient (sun-tracking) w/STS *	62.1 to 62.7	65.9 to 66.6	7.9 to 8.0	-6.1 to -18.0	-117 to -118	52 to 53

Baseline (first row), Baseline (last row)

* no node

MTC Summary

The Man Tended Configuration is easily controllable with the PV arrays locked (either arrow or gravity gradient), but results in significantly reduced power levels.

Sun-tracking MTC without the attached Orbiter (again either arrow or gravity gradient) results in severe attitude controllability problems by virtue of the large variations in moments and products of inertia for all solar geometries encountered during the course of a year.

MTC with attached Orbiter flown in a gravity gradient attitude while fully sun-tracking requires large angular momentum control, and should be studied at other altitudes and solar geometries to assure controllability at all times. Use of the semi-sun tracking strategy would reduce peak angular momentum control requirements with an accompanying 10% reduction in average power levels.

The MTC microgravity environment is acceptable in the arrow flight mode.

Potential solutions for addressing the MTC controllability issues identified include :

Changes to the CMG control law , for example, the use of adaptive gain scheduling, or application of yaw bias techniques, or

Eliminate the root cause of the controllability problem by utilizing alternate sun-tracking strategies, such as the semi-sun tracking technique described, whereby the alpha axis is locked and the beta axis articulates at orbit rate.

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MTC Summary

- **Baselined MTC without Orbiter with locked, feathered arrays is controllable, but results in significantly reduced power levels.**

- **Sun-tracking MTC without Orbiter (either arrow or gravity gradient) results in severe attitude controllability problems.**

- **Baselined MTC with Orbiter in gravity gradient orientation with full sun-tracking is steady state controllable with two CMGs but requires careful CMG control initialization procedures.**

- **The MTC microgravity environment is acceptable in the arrow flight mode.**

- **Potential solutions (MTC without Orbiter) :**

  − Investigate changes to the CMG control law, for example

      Adaptive gain scheduling

      Yaw bias techniques

  − Utilize **alternate sun-tracking strategies** :

      Semi-sun-tracking (beta articulation only) in arrow orientation offers good compromise between power and control.

Technical Assessments

The second half of the study assessed the flight characteristics of the Permanently Manned Configuration (PMC). In particular, the attitude controllability characteristics, both with and without the attached Orbiter, were analyzed in the presence of the geometric asymmetry that results from the use of 3 photovoltaic array pairs.

Again, it is worthwhile to repeat that all attitude control sizing studies studies performed assumed the PDRD *design* atmosphere : solar flux = 230; geomagnetic index = 140 (microgravity environment calculations were performed assuming assembly date nominal atmospheres). All studies were performed assuming an altitude of 220 Nautical miles (except for the Appendix which assumed a 190 Nm altitude)

Technical Assessments

- **Man Tended Configuration (MTC)**
  - Attitude Controllability vs Power Generation Capability
  - With and Without Attached Orbiter

- **Permanently Manned Configuration (PMC)**
  - Attitude Controllability with Asymmetric Geometry
  - With and Without Attached Orbiter

PMC With Asymmetric Power Modules

The restructured Permanently Manned Configuration is characterized by a 56.25 kW power capability provided by three 18.75 kW photovoltaic array pairs. The PV arrays are asymmetrically arranged, with two pairs on the starboard side of the vehicle, and the third pair on the port side, as illustrated. This geometry will give rise to significant aerodynamically induced torques which will have an adverse impact on Torque Equilibrium Attitude, as well as CMG attitude control, which is the subject of the study in this section of the analysis.

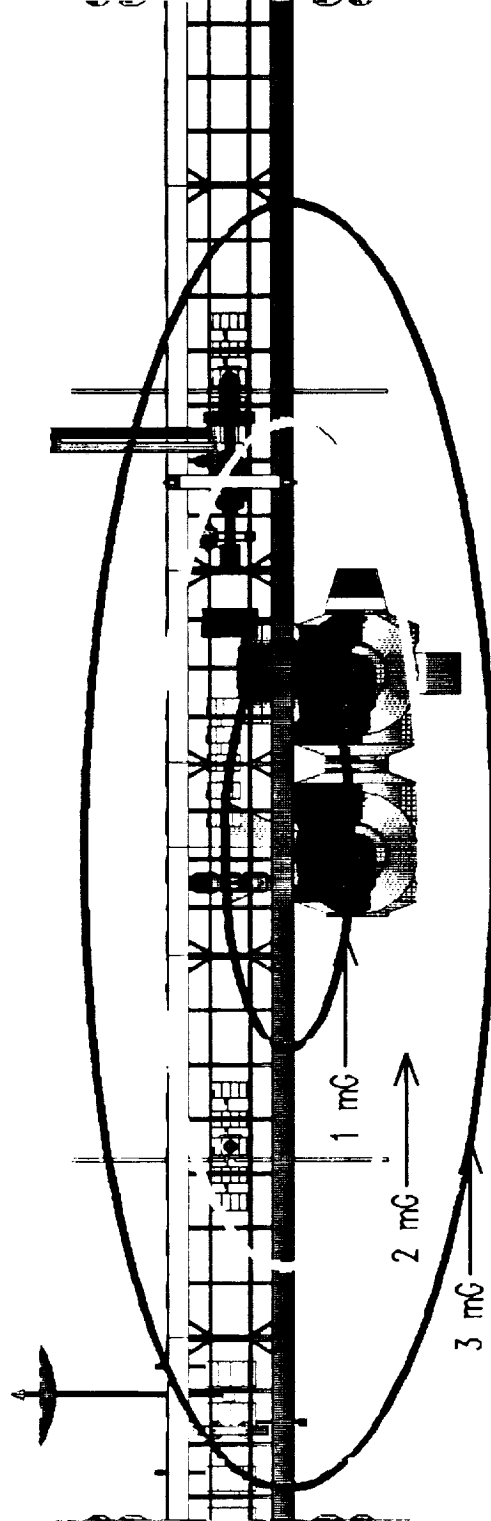# PMC With Asymmetric Power Modules

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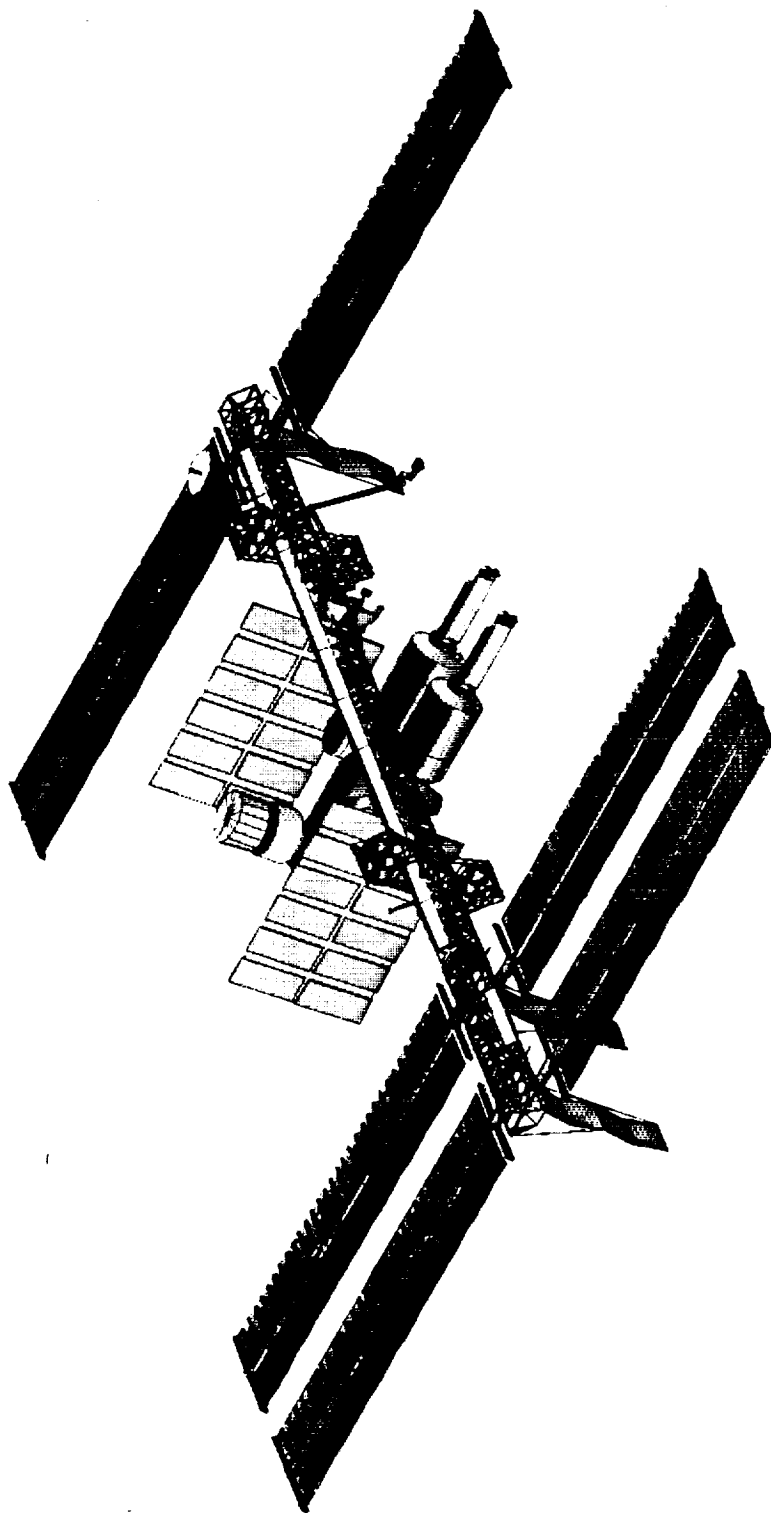
PMC with Asymmetric Power Growth
Micro-G Environment

The microgravity environment for the asymmetric PMC configuration was computed and is illustrated on the page opposite. Nominal atmosphere, altitude (220 Nm), and launch date (June, 1999) were assumed. Shown is the Y-Z plane view, with the velocity coming out of the paper. As can be seen, the pressurized volume falls primarily in the 0 to 2 micro-G range, with a pronounced shift to the starboard side of centerline due to the asymmetric array configuration. Despite the shift, it was judged that the asymmetry did not induce an unacceptable microgravity environment.

PMC with Asymmetric Power Growth

Micro-G Environment

1 mG

2 mG

3 mG

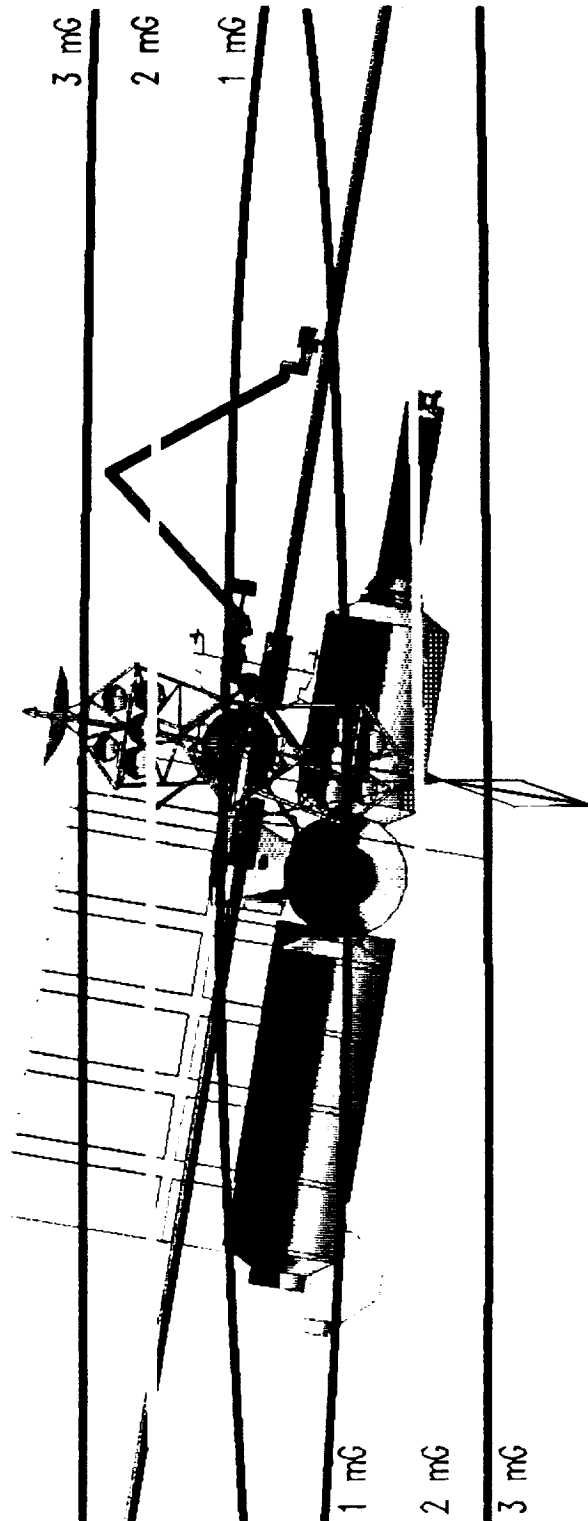Date = 6/99   Alt = 220 nmi
Flux = 135.6   Ap = 13.0

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PMC with Asymmetric Power Growth
Micro-G Environment

This figure depicts the X–Z planar view of the asymmetric PMC configuration (velocity direction to the right). The pitch TEA of –11.4 degrees is evident. The pressurized volume falls primarily in the 0 to 2 micro–G range.

PMC with Asymmetric Power Growth

Micro-G Environment

3 mG
2 mG
1 mG

1 mG
2 mG
3 mG

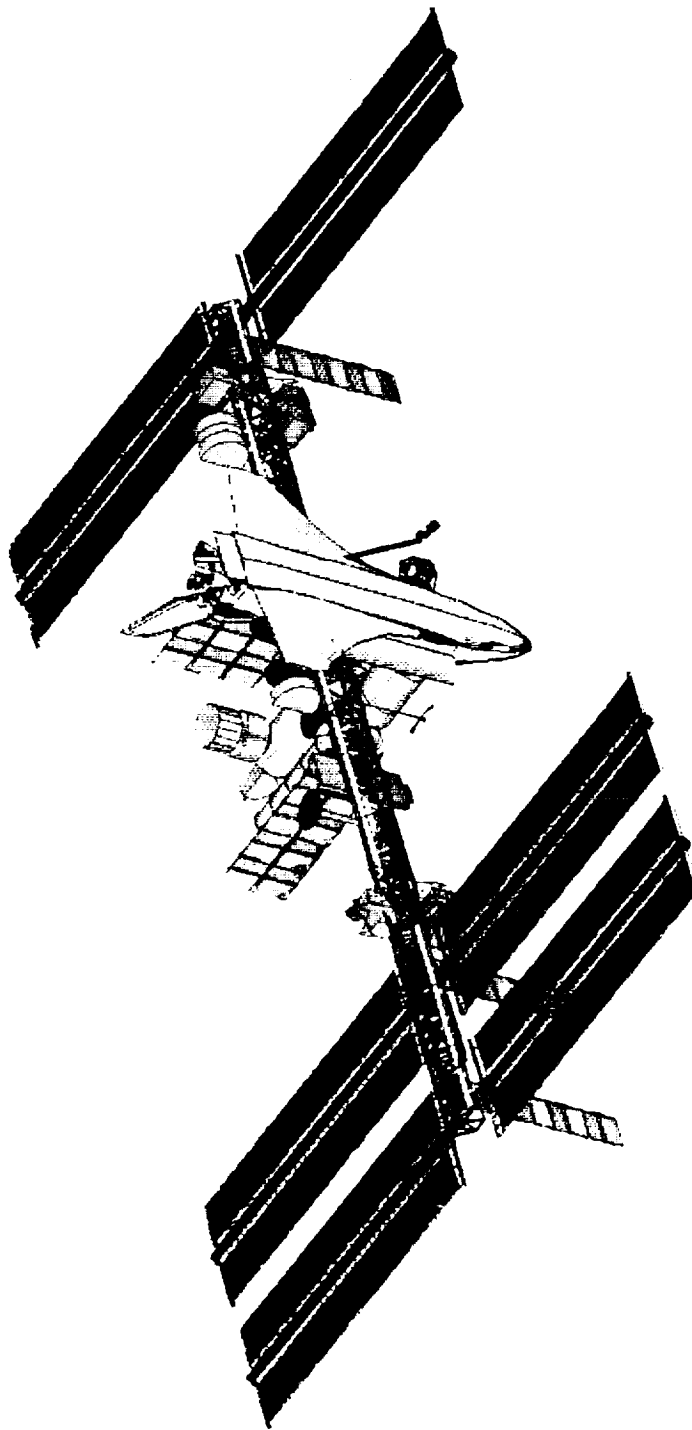| Date = 6/99 | Alt = 220 nmi |
| Flux = 135.6 | Ap = 13.0 |

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PMC With Orbiter on Starboard Side

The figure depicts the asymmetric restructured PMC configuration with the Orbiter attached to the starboard docking mast. in a tail up configuration (due to SRMS reach considerations). Thus the Orbiter is on the same side of the PMC as is the 3rd PV array pair.
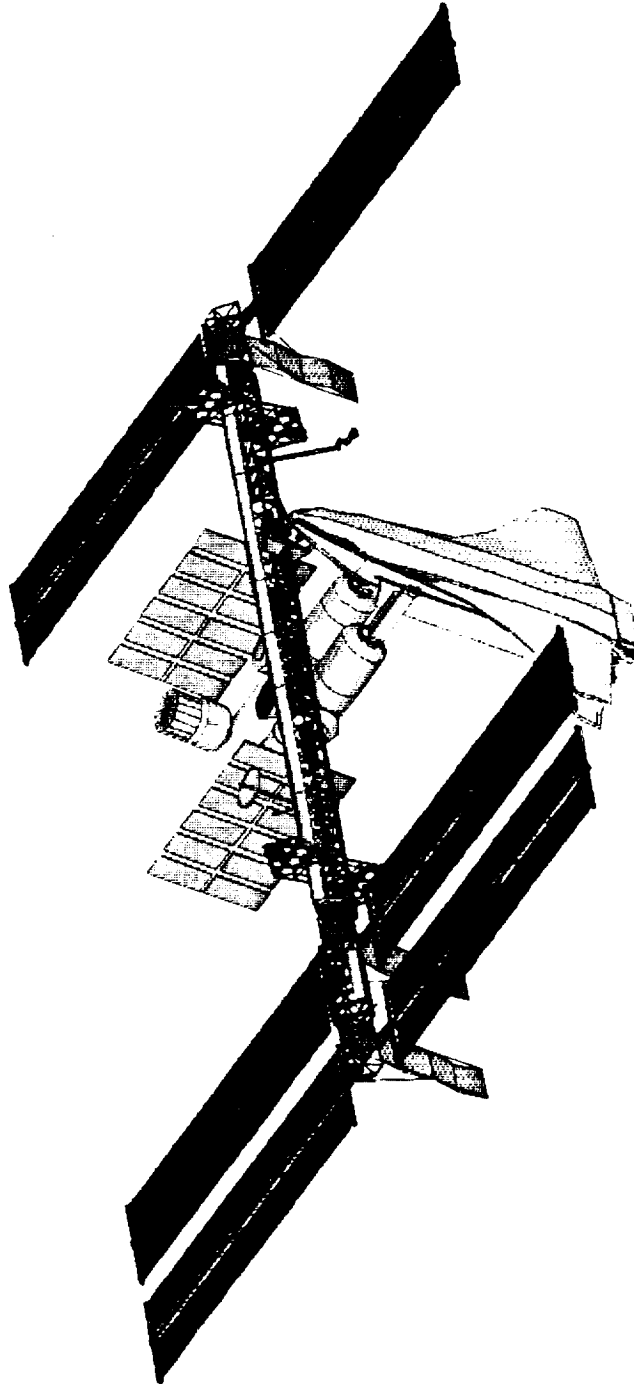
PMC With The Orbiter On Starboard Side

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PMC With Orbiter on Port Side

The figure depicts the asymmetric restructured PMC configuration with the Orbiter attached to the portside docking mast, in a tail down configuration. Thus the Orbiter is on the side opposite of the 3rd PV array pair.

PMC With Orbiter On Port Side

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PMC Control Characteristics

The table opposite summarizes the control characteristics of the PMC configurations studied, both with and without the attached Orbiter. All results were generated assuming a 220 Nm altitude, and design atmosphere (except for microgravity results which assumed nominal day of launch atmosphere)

As expected, the asymmetric configuration has a noticeable yaw TEA of −6.6 degrees due to the unbalanced aerodynamic torque acting on the PV arrays. There is a −11.4 degree pitch TEA for the 220 Nm altitude design atmosphere model simulated. Both the yaw and pitch TEAs are reduced when the outermost PV array is feathered.

The full sun-tracking asymmetric PMC can generate 56.25 kW of power, while the feathered 3rd array PMC case generates an average of only 44 kW.

The ballistic coefficient for the feathered 3rd array configuration is higher (68.8 vs 51.6 Kg/m^2) due to the reduced drag area.

The biggest difference between the two PMC configurations in terms of controllability shows up in the peak angular momentum requirements column. Here it can be seen that the asymmetric configuration requires 14,000 N–m–s angular momentum capacity to maintain attitude, while the feathered PMC configuration requires only 5000 N–m–s (recall that 1 CMG is approximately 4745 N–m–s). The extra control requirements for the asymmetric PMC configuration arise from the large periodic variation in aerodynamic torque about the Z axis.

Steady state attitude rates for the asymmetric PMC are on the order of 0.01 deg/sec. The feathered 3rd array PMC yields attitude rates on the order of $\pm$ 0.002 deg/sec. Anything less than 0.01 deg/sec does not have a major impact on microgravity; any value less than 0.1 deg/sec does not significantly impact rendezvous, docking, and berthing operations.

Both PMC configurations analyzed have similar micro–G environments, on the order of 2 micro–Gs or less.

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Asymmetric PMC Control Characteristics

(3rd pair starboard side)

220 Nm Altitude – Design Atmosphere

Configuration	Avg. Flight Attitude from LVLH (deg) (yaw, pitch, roll)	Avg. Power (kW)	Avg. Ballistic Coef. (kg/m²)	Peak Ang Mom Req'd SS / (max) (N–m–s)	Steady St Angular Rates (deg/sec)	Lab Microg. Environ. (µg)*
Without Attached Orbiter	–6.6, –11.4, 0.6	56.25	51.6	11,000 (14,000)	±0.01	< 2
Feathered 3rd Array	1.3, –8.6, 0.5	43.76	68.8	3000 (5000)	± 0.002	< 2
Orbiter Attached Starboard	–8.0, –42.9, 0.0	56.25	61.1	17,000 (17,000)	±0.01	
Orbiter Attached Port	–14.5, –37.5, 10.0	56.25	59.2	16,000 (19,000)	±0.02	

Large angular momentum requirements for asymmetric PMC

* nominal assembly date atmosphere assumed

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PMC Control Characteristics (continued)

The primary impact of attaching the Orbiter is to significantly increase the pitch TEA, on the order of -40 degrees. In addition, the angular momentum requirements are increased as well. For the case simulated with the Orbiter attached to the starboard side (same side as the 2 array pair), the peak momentum is about 17,000 N-m-s, somewhat larger when compared to the no attached Orbiter PMC. With the Orbiter attached to the port side (opposite of the 2 array pair), the peak angular momentum requirements are closer to 19,000 N-m-s. Docking the Orbiter to either side of the asymmetric PMC configuration increases the angular momentum requirements to values approaching the total CMG capacity of 19,000 N-m-s.

The presence of the Orbiter does not significantly impact the steady state attitude rates.

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Yearly Power Variation for PMC with Asymmetric Power Augmentation Concept with Feathered Outer Arrays

This chart depicts the average annual power available over the period of one year for the feathered outer (3rd) array PMC concept. As can be seen , the lower power bound is 37.5 kW. corresponding to the two array pairs with full sun–tracking. Peak average daily power levels reach as high as 52.3 kW for certain favorable solar geometries. On average. the power level is about 44 kW. Although these results are based upon an assumed LVLH attitude. analysis indicates a relative insensitivity of average power to variations in attitude.

Yearly Power Variation for PMC with Asymmetric
Power Augmentation Concept with Feathered Outer Arrays

Day of the Year

Yearly Power Availability (kW)
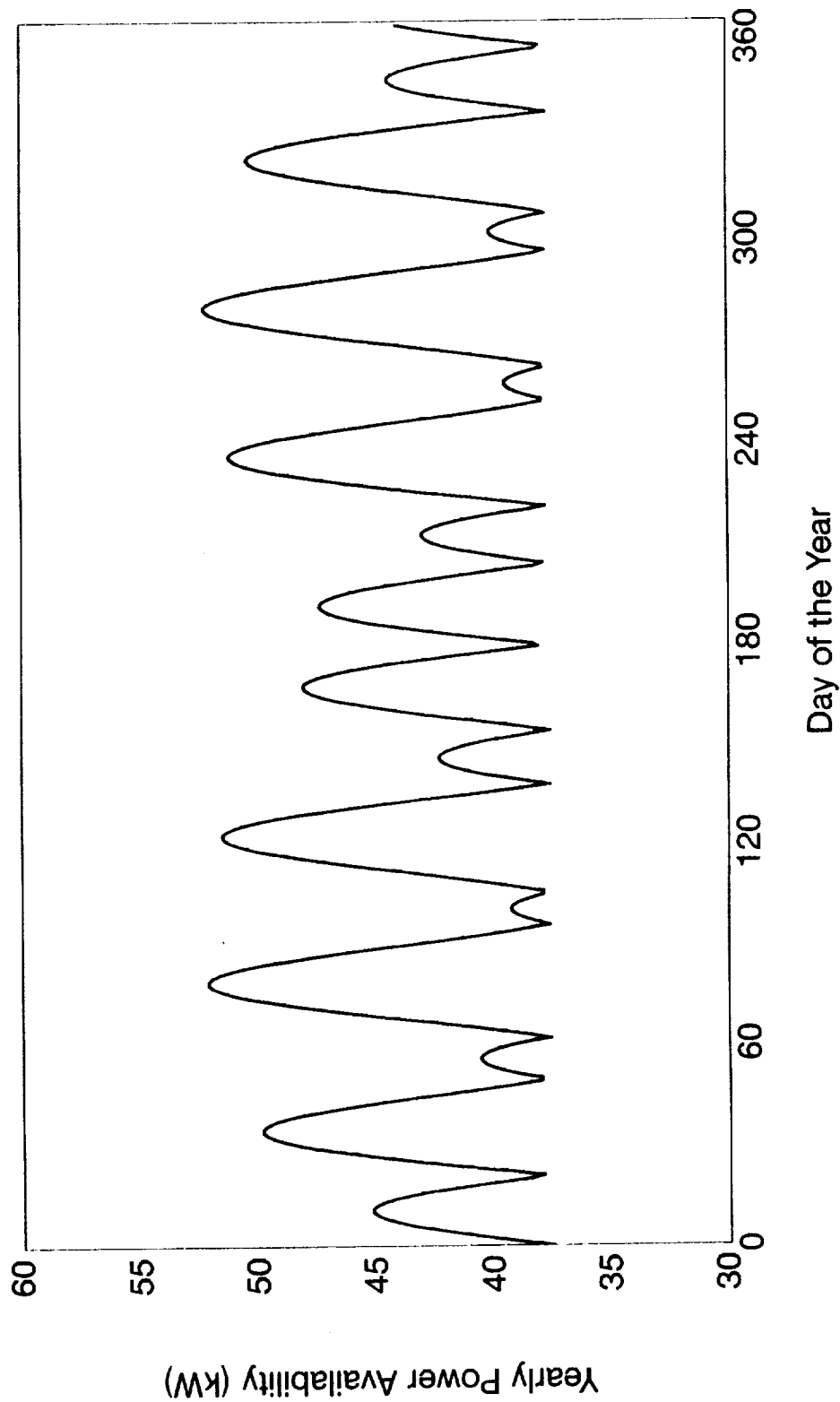
1. LVLH attitude assumed.
2. Yearly average available power is approximately 43.76 kW.
3. Minimum available power is 37.50 kW and maximum available power is 52.27 kW.

Asymmetric PMC Mass Properties
(3rd pair starboard side)

The page opposite summarizes in table form the assumed inertia properties of the asymmetric PMC configuration studied. The values assumed were those used in the accompanying analysis, and are approximate in the sense that they pre-date an official released version of the restructured PMC mass properties.

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Asymmetric PMC Mass Properties

(3rd pair starboard side)

Configuration	Moment of Inertia x10⁷ (Kg–met²)			Product of Inertia x10⁶ (Kg–met²)		
	Ixx	Iyy	Izz	Ixy	Ixz	Iyz
Without Attached Orbiter	8.5 to 8.8	1.0 to 1.2	9.0 to 9.4	1.3 to 1.8	–2.7 to 1.0	–1.1 to –0.6
Feathered 3rd Array	8.5 to 8.7	1.1 to 1.2	9.1 to 9.4	1.5 to 1.8	–2.0 to +0.5	–1.1 to –0.7
Orbiter Attached Starboard	10.2 to 10.6	3.7 to 3.8	10.5 to 10.9	1.4 to 1.6	–7.4 to –10.8	–1.2 to –1.4
Orbiter Attached Port	11.3 to 11.6	4.5 to 4.6	10.8 to 11.2	–4.4 to –4.1	9.7 to 13.5	–7.9 to –7.6

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PMC With 75 Kilowatts

In order to quantify the impact of the PMC asymmetry on the angular momentum control requirements, a fourth pair of PV arrays were added to the existing PMC configuration, thus increasing power capacity to 75 kW. and re-establishing symmetry. The figure opposite depicts the symmetric configuration assessed.

PMC With 75 Kilowatts
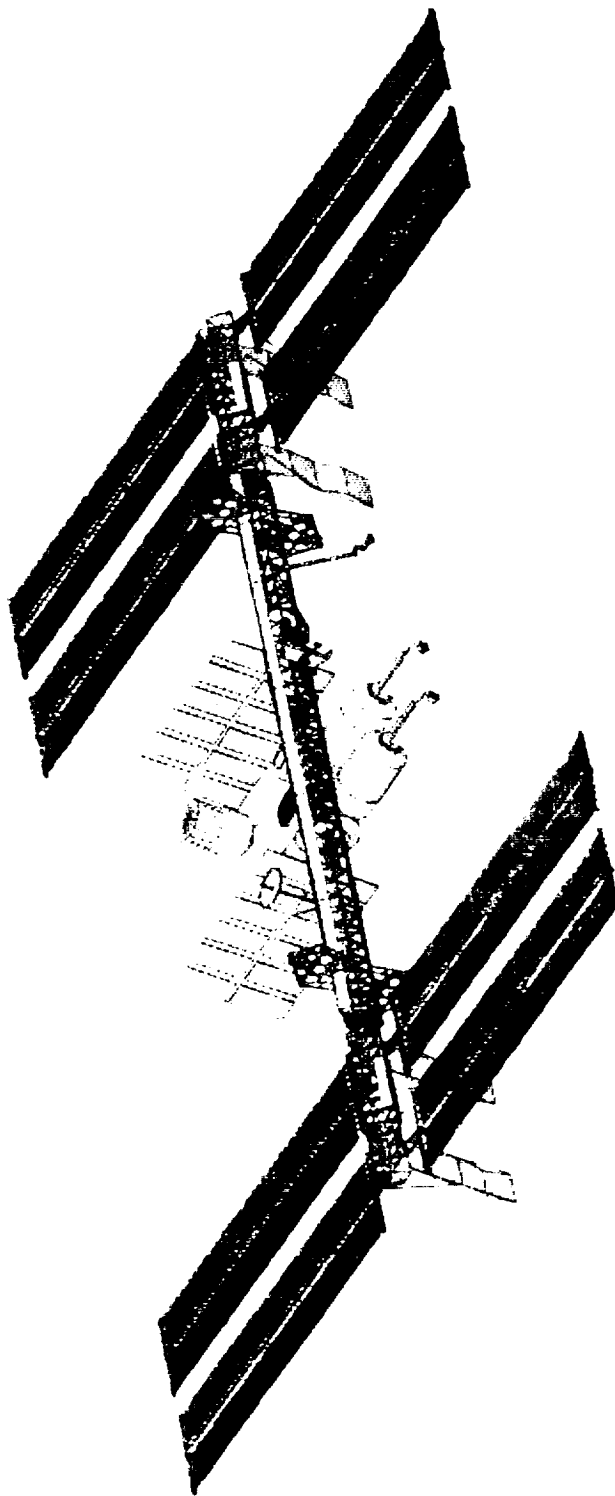
Symmetric vs Asymmetric
PMC Control Characteristics
(no attached Orbiter)

The table compares the asymmetric and symmetric PMC configuration controllability characteristics. The first line of the table repeats the asymmetric results presented earlier, for comparison purposes. The second line corresponds to the symmetric PMC described on the previous page. Notice that the yaw TEA of –6.6 completely vanishes with the addition of the 4th PV array. The additional array does, however, increase the average projected area with respect to the velocity vector, hence, the decrease in ballistic coefficient when compared to the asymmetric PMC. Most significantly, however, is the reduction in peak angular momentum control requirements, which are nearly halved when compared to the asymmetric 56.25 kW configuration. These results clearly indicate that symmetric PMC configurations have lower angular momentum control requirements.

Symmetric vs Asymmetric PMC Control Characteristics

(no attached Orbiter)

220 Nm altitude – Design atmosphere

Configuration	Avg. Flight Attitude from LVLH (deg) (yaw, pitch, roll)	Avg. Power (kW)	Avg. Ballistic Coef. (kg/m^2)	Peak Ang Mom Req'd SS / (max) (N–m–s)	Steady St Angular Rates (deg/sec)	Lab Microg. Environ. (µg)
Asymmetric 56.25 kW 3 pair	–6.6, –11.4, 0.6	56.25	51.6	11,000 (14,000)	±0.01	< 2
Symmetric * 75 kW 4 Pair	0.5, –11.5, 0.2	75.0	44.1	6000 (8000)	<0.001	<2

* PMC with additional (4th) PV array

Symmetric PMC configurations have lower angular momentum requirements compared to asymmetric

SymPMControl

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Symmetric vs Asymmetric
PMC Mass Inertia Properties
(no attached Orbiter)

The page opposite summarizes the mass inertia properties assumed for the PMC configurations analyzed.

Symmetric vs Asymmetric PMC Mass Inertia Properties

(no attached Orbiter)

Configuration	Moment of Inertia x10^7 (Kg–met^2)			Product of Inertia x10^6 (Kg–met^2)		
	Ixx	Iyy	Izz	Ixy	Ixz	Iyz
Asymmetric 56.25 kW 3 pair	8.5 to 8.8	1.0 to 1.2	9.0 to 9.4	1.3 to 1.8	–2.7 to 1.0	–1.1 to –0.6
Symmetric * 75 kW 4 Pair	11.8 to 12.2	1.2 to 1.4	12.3 to 12.8	0.4	–3.3 to 1.7	–0.4

* PMC with additional (4th) PV array

PMC Summary

The concern over the PMC configuration arises from the asymmetric photovoltaic array configuration, resulting from the placement of a 3rd solar panel pair on the starboard side of *Freedom* in order to generate an additional 18.75 kW. In fact, analysis showed a significant aerodynamically induced torque about the yaw axis. Although controllable using CMGs at a 220 Nm altitude, the resulting peak angular momentum requirements are quite large, using most of the CMG capacity just to maintain nominal steady state performance, both with and without the attached Orbiter. It is anticipated that the momentum requirements may increase to a level exceeding CMG control capacity at 190 Nm altitude.

For comparison purposes, a symmetric PMC configuration was also analyzed, whereby a 4th PV wing pair was added to the port side of the configuration. This configuration had much better behaved controllability properties.

Variations in microgravity environment among the PMC configurations studied were minor.

In conclusion, the PMC controllability issues discussed will require resolution either by 1) removing the source of the problem, i.e., the geometric asymmetry identified, or 2) implementing modifications or enhancements to the JSC/UT CMG control laws utilized throughout the analysis presented herein. In particular, *hardware* solutions include 1) an additional array pair to increase power capability and establish symmetry, or 2) additional CMGs to provide the needed control authority. Alternate sun-tracking strategies, such as the feathered 3rd PV array simulation analyzed can be employed, but at the expense of power. Finally, increasing the orbital altitude will reduce the aerodynamic loads, and hence, the CMG angular momentum control requirements on the PMC configuration.

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PMC Summary

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- **Baselined asymmetric PMC results in large steady state and maximum peak CMG angular momentum control requirements (3 to 4 CMGs) both with and without attached Orbiter.**

- **PMC asymmetry does not significantly impact the microgravity environment.**

- **Potential solutions to address CMG angular momentum control requirements :**

  - **Add hardware :**

    Additional pair of PV arrays to provide symmetry (75 kW power)

    Additional CMGs

  - **Utilize alternate sun-tracking strategies :**

    Feathered outboard array results in significantly reduced CMG momentum requirements and 44 kW average annual power

  - **Increase orbital altitude :**

    Increased CMG load due to large asymmetrically induced aero-dynamic torque ; Higher altitude = lower density = lower aero forces.

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APPENDIX

Control Characteristics at 190 Nm Altitude

MTC Control Characteristics

Following presentation of the content of the material discussed in this Technical Memorandum. selected configurations were reassessed assuming an altitude of 190 Nautical miles. which corresponds to the assembly altitude for the MTC and PMC configurations. This altitude represents the highest density atmosphere that the configurations might be expected to encounter. and for which the CMGs must provide adequate attitude control authority.

MTC Control Characteristics

The table opposite summarizes the control characteristics assuming design atmosphere conditions and the JSC/UT controller with regional pole placement technique. The top half of the table (first two lines) repeats the results presented earlier assuming a 220 Nm altitude for the arrow/semi–sun tracking MTC configuration. and the sun–tracking. gravity gradient–attached Orbiter configuration. The bottom half lists the results obtained for the same configurations assuming a 190 Nm altitude.

Somewhat surprisingly. the semi–sun tracking MTC configuration was not controllable at 190 Nm altitude. Evidently. the increased aero torques represented a sufficiently large enough disturbance to cause controllability problems with the CMG algorithm utilized.

For the attached Orbiter case. the peak angular momentum control requirements *tripled*. which exceeded the CMG control capacity. In addition. the peak angular rates were quite large. on the order of $\pm$ 0.04 deg/sec. enough to cause a significant degradation in the microgravity environment.

In summary. the MTC control requirements exceeded the capacity provided by 4 CMGs at 190 Nm altitude assuming the JSC/UT control algorithms using regional pole placement techniques.

MTC Control Characteristics at 190 Nm Altitude

(Design Atmosphere — JSC/UT CMG Controller)

Configuration	Avg. Flight Attitude from LVLH (deg) (yaw, pitch, roll)	Avg. Annual Power (kW)	Avg. Ballistic Coef. (kg/m²)	Peak Ang Mom Req'd SS/(max) (N-m-s)	Peak Angular Rates (deg/sec)
220 Nm					
MTC, Arrow (semi-sun-tracking)	−6.1, −1.0, 0.9	17.0	55.1	2500 (5000)	± 0.02
MTC, Gravity Gradient (sun-tracking) w/STS	4.0, 13.4, 5.4	18.75	79.5	5000 (10,000)	± 0.02
190 Nm					
MTC, Arrow (semi-sun-tracking)	−6.5, −0.8, 1.0	17.0	57.0	uncontrollable	
MTC, Gravity Gradient (sun-tracking) w/STS	3.5, 15.6, 5.5	18.75	78.5	15,000 (30,000)	± 0.04

MTC Control Requirements Exceeded at 190 Nm Altitude

Asymmetric PMC Control Characteristics
190 Nm Altitude (Design Atmosphere)

The table opposite summarizes the results obtained for selected PMC configurations assessed assuming an altitude of 190 Nm, design atmosphere, and the JSC/UT CMG control algorithm using regional pole placement techniques.

The asymmetric PMC peak angular momentum control requirements exceeded the 4 CMG capacity with steady state values in excess of 21,000 N-m-s.

Although increased compared to the 220 Nm simulation, the 190 Nm feathered 3rd array PMC configuration peak momentum requirements were well within CMG capacity.

Both of the attached Orbiter scenarios (starboard tail-up, and portside tail-down) exceeded CMG capacities at 190 Nm altitude. Additionally, steady state angular rates were somewhat large, on the order of .02 to .03 deg/sec.

The symmetric 75 kW PMC configuration angular momentum control requirements were well within the 4 CMG capacity, with peak values less than 10,000 N-m-s.

The conclusion reached from these studies performed assuming a 190 Nm altitude is that the asymmetric 56.25 kW PMC configurations, both with and without attached Orbiter, cannot be controlled with the current 4 CMG capability assuming the utilization of the JSC/UT CMG control law algorithms and regional pole placement techniques.

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Asymmetric PMC Control Characteristics
190 Nm Altitude (Design Atmosphere)

(3rd pair starboard side) (JSC/UT CMG Controller)

Configuration	Avg. Flight Attitude from LVLH (deg) (yaw, pitch, roll)	Avg. Power (kW)	Avg. Ballistic Coef. (kg/m²)	Peak Ang Mom Req'd SS/(max) (N-m-s)	Steady St Angular Rates (deg/sec)
Without Attached Orbiter	−14, −14, 0.0	56.25	49.4	21,000 (30,000)	± 0.025
Feathered 3rd Array	0.1, −13.9, 0.4	43.76	67.3	5000 (6500)	± 0.005
Orbiter Attached Stbd (tail up)	−22, −44.5, 0.5	56.25	58.3	36,000 (36,000)	± 0.02
Orbiter Attached Port (tail down)	−25, −33, 11	56.25	57.2	30,000 (32,000)	± 0.03
75 kW Symmetric	1.0, −14, 0.2	75	43.9	7500 (10,000)	± 0.005

56.25 kW PMC configuration control requirements exceed CMG Capacity using JSC/UT Control Algorithm at 190 Nm

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16. Abstract

In January of 1991, the LaRC SSFO performed an assessment of the configuration characteristics of the proposed pre-integrated Freedom concept. Of particular concern was the relationship of solar array operation and orientation with respect to spacecraft controllability. For the Man-Tended configuration (MTC), it was determined that torque equilibrium attitude (TEA) seeking CMG control laws could not always maintain attitude. The control problems occurred when the solar arrays were tracking the sun to produce full power while flying in an arrow or gravity gradient flight mode. The large solar array articulations that sometimes result from having the functions of the alpha and beta joints reversed on MTC induce large product of inertia changes that can invalidate the control system gains during an orbit. Several modified sun tracking techniques were evaluated with respect to producing a controllable configuration requiring no modifications to the CMG control algorithms. Another assessment involved the Permanently Manned Configuration (PMC) which has a third asymmetric PV unit on one side of the transverse boom. Recommendations include constraining alpha rotations for MTC in the arrow and gravity gradient flight modes and perhaps developing new non TEA seeking control laws. Recommendations for PMC include raising the operational altitude and moving to a symmetric configuration as soon as possible.

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